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Chinese Journal of Aeronautics 23(2010) 670-676
Chinese Journal of Aeronautics
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Integration of Manufacturing Cost into Structural Optimization of Composite Wings

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Received 17 December 2009; accepted 17 May 2010

Abstract

The manufacturing cost is a significant factor that must be considered in the structural design of a composite wing. A multi-objective optimization method for the tradeoff between manufacturing cost and weight of composite wing structure is developed by integrating the manufacturing cost model into the traditional wing structural optimization. A two-level optimization method is proposed to carry out the tradeoff between manufacturing cost and weight, in which the design variables include both structural layout and dimensions and a cost model is incorporated into structural optimization. The manufacturing cost model for a composite wing and the detail procedure for solving this tradeoff problem are presented. The application of the method to the composite wing structural design of an unmanned aerial vehicle is illustrated to verify the method. The application indicates that the method is able to find the Pareto optimal set of minimum structural weight and manufacturing cost. Based on the Pareto optimal set, one can conduct the tradeoff between manufacturing cost and weight of wing structures.

Keywords: wings; composite materials; costs; structure; optimization

1. Introduction

Due to the superior property of composite material, it is evident that the use of composite materials in aircraft structures is increasing for both civil and military aviation industries. The range of application is extended from the secondary components to primary ones in aircraft structural design. The proportional quantity of the use of composite material has even reached more than 90% for some unmanned aerial vehicles (UAVs), which may be called all-composite aircraft[1]. However, further application of composite materials has been restricted by the high costs of raw materials and labors due to intensive manufacturing process[2-3]. To take the cost, designers need tools that will enable them to trade cost against weight and to determine the cost implication in the design process[4-7].

The optimization has been a useful method for structural design[8]. But most of the optimization methods for composite structures focus primarily on the minimization of the structural weight without considering the manufacturing cost[9-10]. The aim of this article is to propose a structural optimization method that enables designers to obtain a more reasonable design by the tradeoff between manufacturing cost and weight of wing structure during preliminary design phase. Since the wing structural layout has a significant impact on the cost, the structural layout must be considered for this tradeoff. The unique features of this article are: 1) design variables include both structural layout and dimensions; 2) a cost model is incorporated into structural optimization.

2. Cost Estimation Model

The manufacturing cost models can be generally classified into two categories: 1) parametric cost models (PCMs), and 2) manufacturing process cost models (MPCMs)[11-12]. The MPCMs are constructed according to the detailed estimations of the main categories of manufacturing cost such as raw material, and assembling and supporting labor hours. The cost drivers are analyzed at the manufacturing process level. Ac-

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Foundation item: NUAA Research Funding (NJ2010006)

doi: 10.1016/S1000-9361(09)60269-7

cordingly, the MPCMs have the advantages of recognizing the impacts of design changes, process selection and even material types on the cost and especially being suitable for new design and technology. The MPCMs are usually more accurate than the PCMs in the structural design of aircraft. In this article, the MPCM is used to estimate the cost of a composite wing.

The manufacturing process cost model is based on the first-order velocity model. According to this model, the total process of fabrication is divided into sub-operations. Each sub-operation is represented by a first-order velocity expression as follows[13]:

$$v = v_0(1-\mathrm{e}^{-t/\tau_0}) \tag{1}$$

where v_0 is the steady-state process velocity, τ_0 the dynamic time constant, and t the process time.

In general, the process time is driven by the major geometric character of a part, such as its surface area, length or volume. This character is given by the variable named L, which may be the fabrication areas of skin, spars and ribs, and the assembling perimeter of wing. The process velocity v can be equated to the first derivative of L with respect to t. The integration and approximation of Eq.(1) lead to[14-15]

$$t = \sqrt{(L/v_0)^2 + (2L\tau_0/v_0)} \tag{2}$$

Once the manufacturing process is defined, every sub-process time can be also determined in the model, where the values of parameters v_0 and τ_0 can be found in Ref.[16] and are given in Table 1. The process time t consists of the fabrication time and assembling time. The process time leads to the fabrication cost when it is multiplied by the hourly rate of labor. The equation is as follows:

$$C_\mathrm{p} = (t_\mathrm{f} + t_\mathrm{a})P_\mathrm{l} \tag{3}$$

where C_p is the fabrication cost of a part, t_f the time of fabrication, t_a the time of assembling, and P_l the labor cost. The total fabrication cost of a composite wing is the sum of the fabrication costs of all parts.

Table 1 Cost parameters for parts of composite wing

Item	v_0/ ($\mathrm{cm^2 \cdot min^{-1}}$)	τ_0/min	Characteristic of design variable
Skin fabrication	13.833 3	4.388 3	Area, $\mathrm{cm^2}$
Spar fabrication	9.342 8	6.278 8	Area, $\mathrm{cm^2}$
Rib fabrication	5.312 2	10.356	Area, $\mathrm{cm^2}$
Wing assembling	0.071 78	2.987 7	Assembling perimeter, cm

Materials used in the fabrication of a part consist of two types: consumables and part material. The amount of the material being used is transformed into actual cost using the unit price of the material. The cost estimation formula is

$$C_\mathrm{m} = L(1+s)P_\mathrm{m} \tag{4}$$

where C_m is the material cost of a part, s the scrapping rate, and P_m the material price per unit area, length or volume. The material costs of all parts are summed up to get the total material cost of a composite wing.

The cost of the wastage of machinery, equipment and tools during fabrication is not taken into account in this article.

If the number of parts is N, the total manufacturing cost of composite wing C_W consists of the total fabrication cost and the total material cost, that is

$$C_\mathrm{W} = \sum_{i=1}^{N}(C_\mathrm{p}^i + C_\mathrm{m}^i) \tag{5}$$

where C_p^i and C_m^i are the fabrication cost of and the material cost of the ith part, respectively.

If the geometric features of wing structure such as part area or assembling perimeter are found, the manufacturing cost of the wing can be estimated through the above mentioned cost model.

The above mentioned process-based cost estimation model can be used to estimate the cost of the component in the preliminary design phase of aircraft when the computer aided design (CAD) model is defined. Once the manufacturing process is defined, the sequence of processing and the time constants appropriate to a particular manufacturing facility can be imbedded automatically in the model.

3. Optimization Problem and Method

The layout of a wing structure is depicted in Fig.1. The function of wing structure is bearing the aerodynamic loads. All the bending loads are carried by the spars; the torsion loads are carried by the wing box which is constituted by the skin and the front and rear spar webs; and the shearing loads are carried by the front and rear spar webs. The design task is to determine the layout and dimensions of the wing structure through the tradeoff between manufacturing cost and weight.

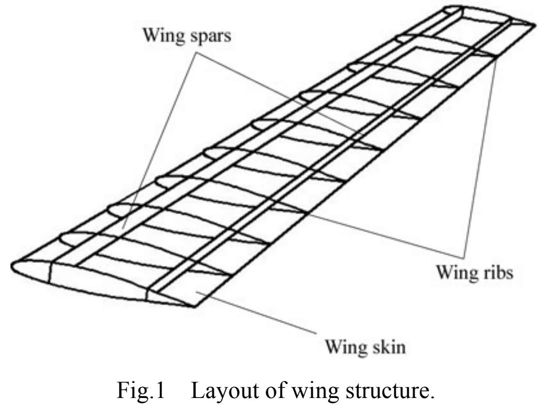

Fig.1 Layout of wing structure.

The tradeoff between manufacturing cost and weight of wing structure can be stated as a multi-objective optimization problem as follows.

Objective Minimized structural weight W_S and manufacturing cost C_W.

Constrains The strength requirements, displacement constraints, failure criteria and buckling criteria.

Design variables The layout variables of wing structure $\boldsymbol{X}_1$, including the number of spars, the number of ribs, and the locations of the front spar and the rear spar; and the structural dimensions $\boldsymbol{X}_2$, including the thicknesses of the skin, spar webs and rib webs, and the sectional area of the bars.

The two-level approach[17] is used to solve the trade-off problem. The problem can be decomposed into following two level optimization problems: 1) the layout optimization at system level; 2) the structural dimensions optimization and the cost analysis at subsystem level, as shown in Fig.2.

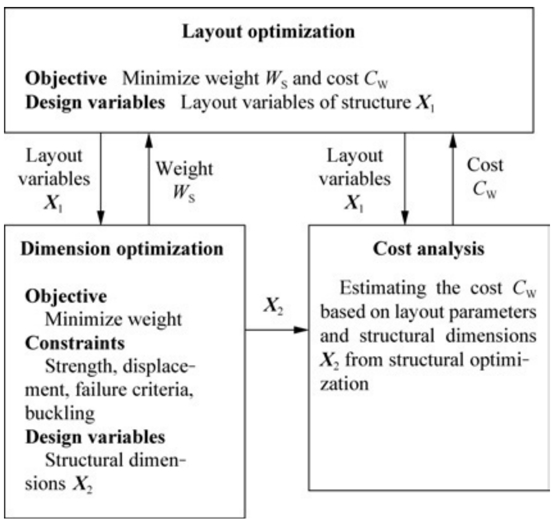

Fig.2 Two-level optimization method.

The layout optimization is a multi-objective optimization problem in which the objective is to minimize both manufacturing cost and weight, and the design variables are the layout variables $\boldsymbol{X}_1$ at the system level.

At structural dimension optimization level, the objective is to minimize the weight of wing structure, and the design variables are the structural dimensions $\boldsymbol{X}_2$. The layout design variables are fixed parameters at this level. The constraints include the local stress or strain, the displacement of wing tip, failure criteria and bucking criteria. When the structural dimension optimization is completed, the structural weight W_S is fed back to the layout optimization level and the values of the structural dimensions $\boldsymbol{X}_2$ are transmitted to the cost analysis model.

Given the values of the layout variables $\boldsymbol{X}_1$ and structural dimensions $\boldsymbol{X}_2$ of the wing, its manufacturing cost can be obtained using the cost estimation model presented in Section 2. The value of the cost C_W is then fed back to the layout optimization level.

By iteration between the layout optimization and dimension optimization and cost analysis, the Pareto optimal set for minimum weight and cost can be found through a multi-objective optimization algorithm. Based on the Pareto optimum set, one can trade the cost against the weight of the wing structural design.

4. Implementation Procedure

Following the two-level optimization method proposed above, a detail procedure for the integration of manufacturing cost into the wing structural optimization is shown as a flowchart and depicted in Fig.3. Each step in this flowchart will be explained below.

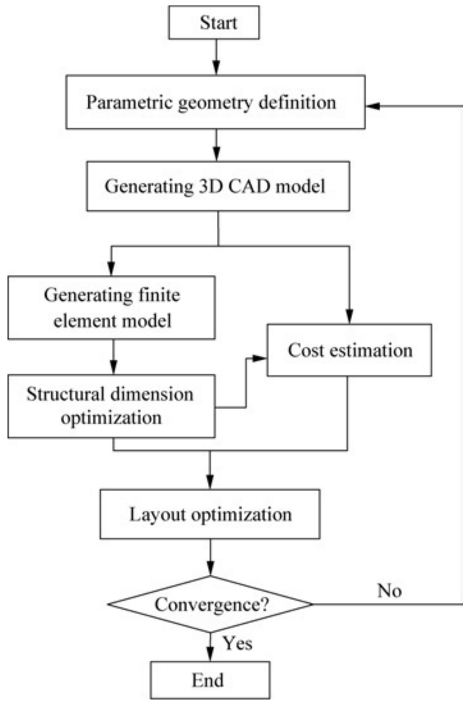

Fig.3 A flowchart for integration of cost model into structural optimization.

(1) Parametric geometry definition

A set of parameters, which represent the external shape and the structural layout are defined. The parameters for the wing external shape definition are the area, the aspect ratio, the taper ratio, the sweep angle, and the airfoil. The parameters for the structural layout include the number of spars, the number of ribs, and the locations of the front spar and the rear spar. The parameters for structural layout are taken as the design variables and will be changed during layout optimization.

(2) Generating 3D CAD model

Based on the parameters defined above, a CAD model of the wing structure is automatically generated by the geometric model generator[18]. The geometric model generator is a Microsoft Visual Basic (VB) routine that has an interface with Computer Graphics Aided Three Dimensional Application (CATIA) software. With this VB routine, the 3D CAD models of structure for different layouts can be generated, in which the intersections of the spars, ribs, and skin are split automatically, the struts are built at the intersections of the spar webs and rib webs, the front and rear edges of the wing are removed, and only the wing box is reserved. By use of the VB routine, the geometry mis-matching is avoided when the CAD model is imported to the software of the finite element method (FEM). An example of the CAD model of the wing structure generated by the geometric model generator is shown in Fig.4. The geometry model of the wing box can be generated automatically by the model generator with the format of initial graphics exchange standard (IGES) which can be imported to the software MSC Patran/Nastran.

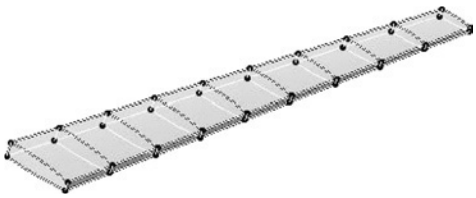

Fig.4 A CAD model of a wing box.

(3) Generating finite element model

By using Patran Command Language (PCL) of MSC Patran/Nastran software, the CAD model is to be imported to the software MSC Patran/Nastran, and a finite element model for the wing box is generated automatically. The initial value of the structural dimensions, the information of material, the degree of freedom (DOF) constraints, and the aerodynamic loads are defined using PCL in the finite element model. The parameters for structural dimensions are the thickness of the skin, the thicknesses of the spar webs and the ribs, and the sectional area of the bars. The initial dimensions of the structure are given based on the previous experience. An example of the finite element model of the wing structure generated by PCL is shown in Fig.5. In the finite element model of the wing structure, the skin, spar webs and rib webs are modeled by shell elements, and the flanges of spars and ribs are modeled by rod elements.

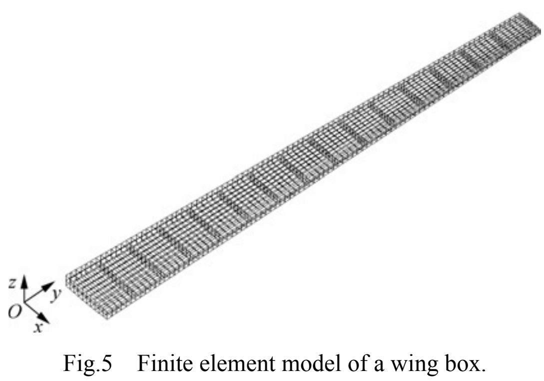

Fig.5 Finite element model of a wing box.

(4) Structural dimension optimization

After the finite element model of the wing structure is generated, the structural dimension optimization is carried out. Its task is to find the dimensions of structural elements with minimum weight under the constraints of the allowable stress or strain of all materials, and the structural deformation and bucking criteria. In addition, the composite failure criterion (Tsai-Hill failure criterion) is also used as a constraint for composite wing design.

The structural dimension optimization is implemented with software MSC Patran/Nastran. After the optimization, the values of the structural dimensions are transmitted to next step, i.e. the manufacturing cost estimation.

(5) Cost estimation

To estimate cost, the geometric features such as the fabrication areas of skin, spars and ribs, and the assembling perimeter of the wing are needed. A VB-CATIA script is developed to extract those geometric features from the 3D CAD model of the wing structure. Fig.6 shows a geometric model for wing cost estimation. Based on the geometric features and the dimensions of structure, one can estimate the manufacturing cost of the wing using the cost estimation model mentioned in Section 2.

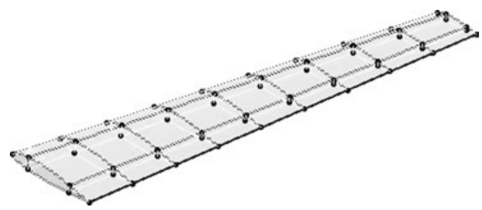

Fig.6 A geometric model for wing cost estimation.

(6) Layout optimization

When the above steps are finished, the values of weight and cost are computed for a layout design of wing structure. The task of structural layout optimization is to find the Pareto optimal set for the wing structural layouts with minimum weight and cost. This multi- objective optimization problem can be solved by genetic algorithms, such as the non-dominated sorting genetic algorithm (NSGA-II)[19]. During the structural layout optimization, the structural dimension optimization and the cost analysis are repeated until the convergence is satisfied.

The above mentioned procedure indicates that the common CAD model is provided to both structural dimension optimization and cost estimation. All the steps can be integrated using the software iSIGHT[20]. The overall process is executed automatically.

5. An Application Example

A structural design optimization for the composite wing of a UAV is used as an example to verify the applicability of the proposed method.

5.1. Description of design problem

The cruise Mach number of the UAV is 0.7. The cruise altitude is 10 600 m. The takeoff weight of the UAV is 1 580 kg. The external shape of the wing is defined as follows: the area of the wing is 6.5 m^2, the aspect ratio is 10.0, the taper ratio is 0.5, and the sweep angle is 12°.

For the structural layout, two or three spars can be applied. The initial positions, the lower and upper values for the front and rear spars are listed in Table 2. For the wing with 3 spars, the third spar is located at the middle between the front spar and rear spar. The number of the ribs ranges from ten to twenty. The spacing of the ribs is uniform along span. The variables of the structural layout are listed in Table 2.

Table 2 Design variables of structural layout

Variable	Initial value	Lower value	Upper value
Number of spars	2	2	3
Number of ribs	12	10	20
Location of front spar	0.15	0.10	0.25
Location of rear spar	0.65	0.60	0.75

The aerodynamic load is computed by the computer program FLO22[21], which is based on the full potential equation. The operating overload factor is 3.0 in this example and the safety factor is 1.5.

The Carbon/Epoxy T300/5208 material is used for all parts of the composite wing. The material ply orientations are limited to −45°, 0°, 45°, and 90°. The plies are symmetric for all parts. The mechanical properties of the material are obtained from Ref.[22] and is given in Table 3. Where E_1 is the elastic modulus in the fiber direction, E_2 the elastic modulus in the transverse direction, G_{12} the longitudinal shear modulus, v_{12} the Poisson's ration, ρ the weight density, X_t and X_c are the tensile strength and the compressive strength in the fiber direction, respectively, Y_t and Y_c the tensile strength and the compressive strength in the transverse direction, and S is the shear strength. The market price of the material is RMB 700 yuan per square meter. The thickness of the material is 0.1 mm for each layer. The wing box is manufactured by the co-curing process. The skins of leading and trailing edges are cemented into the wing box. The labor rate is assumed as RMB 60 yuan per hour. The scrapping rate is 0.4 based on the previous experience when the first wing is fabricated.

Table 3 Material properties of Carbon/Epoxy T300/5208

Property	Value	Property	Value
E_1/GPa	185	X_t/MPa	1 500
E_2/GPa	10.3	X_c/MPa	1 500
G_{12}/GPa	7.17	Y_t/MPa	40
v_{12}	0.28	Y_c/MPa	246
ρ/(g·cm^{-3})	1.76	S/MPa	68

The design variables in dimension optimization are the thickness of skin and web. The wing structure is divided into three sections along wing span. Each section consists of the upper skin, lower skin, spars and ribs. The thicknesses of the parts (upper skin, lower skin, spar webs and rib webs) are identical for same section, but are variable for different sections. Each section has four design variables describing the thickness of each ply orientation. The total number of variables is 60 when the wing has two spars.

The formulation of the structural optimization is stated as follows.

Find:
    numbers of the spars and ribs
    locations of the spars
    thicknesses of the skin
    thicknesses of the spar webs and rib webs
    sectional areas of the bars
Minimize:
    structural weight and cost
Be subject to:
    stress ≤ 450 MPa
    displacement of wing tip ≤5% of wing span
    $\lambda \geq 1$ (buckling criterion)
    F.I<1 (Tsai-Hill failure criterion)
    $x_{i,\min} \leq x_i \leq x_{i,\max}$ (dimension constraint)

where λ is the buckling coefficient, F.I the invalidation coefficient, x_i the dimension variables, $x_{i,\min}$ the lower dimension value, and $x_{i,\max}$ the upper dimension value.

This design problem is solved by the procedure presented in Section 4. At the layout optimization level, NSGA-II is employed to obtain the Pareto optimal set for minimum weight and cost. Since the structural analysis which takes the buckling criterion into account is time-consuming, the population size and the number of generations of NSGA-II are limited to the reasonable values so that the Pareto optimal set can be obtained within acceptable period of time. For this example, the population size is set as 20, and the number of generations is 20.

5.2. Results

The Pareto optimal set for the minimum structural weight and manufacturing cost is obtained and shown in Fig.7.

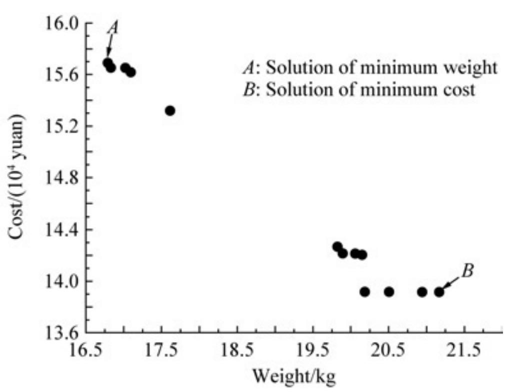

Fig.7 Pareto optimal set for weight and cost.

The solution A is the structural design with minimum weight, which consists of 3 spars and 11 ribs. The front and rear spars are located at 24.20% and 61.13% of the local chords, respectively. The weight is 16.79 kg and the cost is RMB 156 900 yuan.

The solution B is the design with minimum cost, which consists of 2 spars and 10 ribs. The front spar and rear spar are located at 23.86% and 60.61% of the local chords, respectively. The weight is 21.17 kg and the cost is RMB 139 100 yuan.

Comparing the solution A with solution B, one can find that the solution A has more spars and ribs, and its weight is reduced by 11.34%, but its manufacturing cost is increased by 26.1%. The comparison implies that with more spars and ribs can reduce the weight for a composite wing structure with this manufacturing process, but will result in higher cost. In other hand, with less spars and ribs can reduce the cost of the wing structure, but will lead to weight growth.

The typical Pareto solutions obtained are listed in Table 4, in which different structural layouts are corresponding to different weights and costs. One can select the appropriate structural layout from the Pareto optimal set through the tradeoff between the weight and manufacturing cost of the wing structure.

Table 4 Typical Pareto solutions

Number of ribs	Number of spars	Location of front spar	Location of rear spar	Weight/ kg	Cost/ (10^4yuan)
11	3	0.240 5	0.606 8	17.02	15.65
10	2	0.238 6	0.606 2	20.19	13.92
10	2	0.243 0	0.610 8	20.51	13.92
11	2	0.242 0	0.611 0	19.83	14.27
10	3	0.238 2	0.606 2	17.61	15.32
11	3	0.240 5	0.604 5	17.10	15.62
11	2	0.240 9	0.606 1	19.89	14.22
11	3	0.242 0	0.611 3	16.79	15.69

6. Conclusions

A method of integrating the manufacturing cost model into the traditional wing structural optimization for composite wing structure is developed and used to conduct tradeoff between manufacturing cost and weight. The key points are summarized as follows.

(1) The two-level optimization method for the tradeoff between manufacturing cost and weight of composite wing structure is proposed. Both layout and dimensions of wing structure are taken as design variables.

(2) A detail procedure implementing the method is presented. The practical technique is that the structural analysis model and cost analysis model are automatically generated from a common parametric wing CAD model. All the steps can be integrated by using the software iSIGHT.

(3) The application of this method to the composite wing structure of a UAV manifested that the method is able to find the Pareto optimal set of minimum structural weight and manufacturing cost. Based on the Pareto optimal set, the tradeoff between manufacturing cost and weight can be carried out.

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